Astronomy & Astrophysics manuscript no. bekkig1 February 2, 2008
(DOI: will be inserted by hand later)

Formation of giant globular cluster G1 and the origin of the M31 stellar halo

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Received 20 September 2003/ Accepted 21 Octorber 2003

Abstract. We first demonstrate that globular cluster G1 could have been formed by tidal interaction between M31 and a nucleated dwarf galaxy (dE,N). Our fully self-consistent numerical simulations show that during tidal interaction between M31 and G1's progenitor dE,N with $M_{\rm B} \sim -15$ mag and its nucleus mass of $\sim 10^7$ $M_{\odot}$, the dark matter and the outer stellar envelope of the dE,N are nearly completely stripped whereas the nucleus can survive the tidal stripping because of its initially compact nature. The naked nucleus (i.e., G1) has orbital properties similar to those of its progenitor dE,N. The stripped stars form a metal-poor ([Fe/H] ~ -1) stellar halo around M31 and its structure and kinematics depend strongly on the initial orbit of G1's progenitor dE,N. We suggest that the observed large projected distance of G1 from M31 ($\sim$ 40 kpc) can give some strong constraints on the central density of the dark matter halo of dE,N. We discuss these results in the context of substructures of M31's stellar halo recently revealed by Ferguson et al. (2002).

Key words. galaxies: halos — galaxies: individual (M31) — galaxies: interactions — galaxies: star clusters — globular clusters: individual (ω Centauri, Mayall II = G1)

1. Introduction

A growing number of photometric and spectroscopic observations have suggested that G1 (=Mayall II), which is one of the brightest globular clusters belonging to M31, has very unique physical properties as a globular cluster (e.g., Meylan et al. 2001). These include a possible intrinsic metallicity dispersion among its stellar population (Meylan et al. 2001), the large central velocity dispersion of $\sim$ 25 km s^{-1} (e.g., Djorgovski et al. 1997), the very flattened shape with mean ellipticity of 0.2 and significantly high central surface brightness (Rich et al. 1996; Meylan et al. 2001), and the possible existence of a black hole with a mass of 20000 $M_{\odot}$ (Gebhardt et al. 2002). In spite of its extraordinary nature, G1 is observed to be on the $M_{\rm V}$-σ_0 relation (where $M_{\rm V}$ and σ_0 are total magnitude in $V-$band and central velocity dispersion) defined not by elliptical and dwarf galaxies but by globular clusters, which implies that G1 looks like a genuine globular cluster (Meylan et al. 2001).

One of the possible scenarios of G1 formation is that G1 is the surviving nucleus of an ancient nucleated dwarf galaxy with its outer stellar envelope almost entirely stripped by M31's strong tidal field (Meylan et al. 1997, 2000, 2001). Such a scenario has already been suggested by Zinnecker et al. (1988) and Freeman (1993), and the viability of the scenario has been extensively discussed by many authors in terms of ω Cen formation (e.g., Hilker & Richtler 2000; Dinescu 2002; Gnedin et al. 2002; Zhao 2002; Bekki & Freeman 2003; Mizutani et al. 2003). However, no theoretical attempts have been made so far to investigate (1) whether M31's tidal filed is strong enough to transform a dE,N into G1 and (2) what observable evidence of the past destruction of G1's progenitor dE,N we can find in the M31 halo regions. The above point (2) is very important, because Ibata et al. (2001) and Ferguson et al. (2002) have recently discovered M31's stellar halo substructures, which could have been formed from tidal destruction of M31's satellite dwarfs.

In this paper, by using numerical simulations, we first demonstrate that G1 can be formed from a dE,N during tidal interaction between the dE,N and M31. Our fully self-consistent numerical simulations demonstrate that the stellar envelope of dE,N with $M_{\rm B} \sim -15$ can be nearly completely stripped by the strong tidal field of M31 whereas the central nucleus can remain intact owing to its compactness. We suggest that this naked nucleus orbiting M31 is a giant globular cluster (i.e., G1). The morphological transformation from dE,Ns into very compact stellar systems was originally investigated by Bekki et al. (2001, 2003) for ultra-compact dwarfs labeled as "UCD" (Drinkwater et al. 2003) and called "galaxy threshing" (Bekki et al. 2001), though they suggested that galaxy threshing is also important for the formation of giant globular clusters such as ω Cen and G1. The present study confirms this early suggestion

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and discusses the physical relationship between UCDs, ω Cen, and G1.

2. Model

Since our numerical methods and techniques for modeling collisionless, self-gravitating systems of dE,Ns already have been described in detail by Bekki et al. (2003), we give only a brief review here. We consider that a dE,N with a mass and size similar to that observed for the dE,N types orbiting M31. The dE,N is modeled as a fully self-gravitating system and is assumed to consist of a dark matter halo, a stellar component and a nucleus: We first investigate this "three-component" dE,N model. For convenience, the stellar component (i.e., the main baryonic component) is referred to as either the "envelope" or the "stellar envelope" so that we can distinguish this component from the stellar nucleus. The density profile of the dark matter halo with the total mass of $M_{\rm dm}$ in the dE,N is represented by that proposed by Salucci & Burkert (2000):

$$\rho_{\rm dm}(r) = \frac{\rho_{dm,0}}{(r + a_{\rm dm})(r^2 + a_{\rm dm})^2}, \quad (1)$$

where $\rho_{dm,0}$ and $a_{\rm dm}$ are the central dark matter density and the core (scale) radius, respectively. This model profile is consistent with observations and different from the predictions of the standard CDM model (Navarro, Frenk, & White 1996, hereafter NFW). The dark matter core parameters, $\rho_{dm,0}$, $a_{\rm dm}$, and M_0 (where M_0 is the total dark matter mass within $a_{\rm dm}$) have a clear observed correlation, $M_0 = 4.3 \times 10^7 (\frac{a_{\rm dm}}{\rm kpc})^{7/3} M_{\odot}$ (Burkert 1995).

The mass (luminosity) and the scale length of the stellar envelope of the dE,N is modeled according to the observed scaling relation of Ferguson & Binggeli (1994):

$$\log a_{\rm dw}[{\rm pc}] = -0.02 M_{\rm B} + 2.6 \quad (2)$$

for faint dwarfs ($M_{\rm B} \geq -16$), where $a_{\rm dw}$ and $M_{\rm B}$ are the scale length of the exponential profile and the absolute B−band magnitude, respectively. The projected density of the envelope with $M_{\rm B}$ and the total mass of $M_{\rm dw}$ (and $M_{\rm dw}/L_{\rm B} = 2$) is represented by an exponential profile with a scale length $a_{\rm dw}$. The projected density profile of the nucleus with mass $M_{\rm n}$ is represented by a King model (King 1964) with a core radius of $a_{\rm n}$ and a central concentration parameter c of 1.0.

The nuclei typically contribute about a few percent of the total light of dwarfs (Binggeli & Cameron 1991; Freeman 1993) and the present-day mass of G1 is estimated to be 1.5×10^7 $M_{\odot}$ for the King model (Meylan et al. 2001). Considering these observations, the reasonable $M_{\rm B}$ of dE,N is estimated to be ~ -15 mag. Given a value of $M_{\rm dm}/M_{\rm dw}$, we can determine $a_{\rm dm}$ from the above M_0-$a_{\rm dm}$ relation (Burkert 1995). For convenience, $a_{\rm dm}$ for $M_{\rm B} = -15$ mag and $M_{\rm dm}/M_{\rm dw} = 5$ is referred to as $a_{\rm dm,0}$ hereafter. We mainly investigate the dE,N models with $M_{\rm B} = -15$ mag, $a_{\rm dw} = 790$ pc, $M_{\rm dm}/M_{\rm dw} = 5$, $a_{\rm dm} = a_{\rm dm,0}$, $M_{\rm n}/M_{\rm dw} = 0.05$, and $a_{\rm n}/a_{\rm dw} = 0.02$. All of these values are reasonably consistent with observations (Binggeli & Cameron 1991; Ferguson & Binggeli 1994). We also investigate the models with $a_{\rm dm} = 0.25 a_{\rm dm,0}$ to clarify the importance of the dark matter halo structure of a dE,N in the formation processes of G1.

Table 1. Model parameters

model	$a_{\rm dm}/a_{\rm dm,0}$	$\theta(degrees)$	$R_{\rm apo}(kpc)$	$e_{\rm p}$
fiducial	1.0	30	80	0.62
smaller $e_{\rm p}$	1.0	30	80	0.18
smaller $R_{\rm apo}$	1.0	30	40	0.62
more compact dark matter	0.25	30	80	0.62

M31 is assumed to have the disk mass of 7.8×10^{10} $M_{\odot}$, and the bulge-to-disk-ratio of 0.25, and the maximum rotational velocity of 260 km s^{-1}, all of which are consistent with observations (e.g., van den Bergh 2000). The initial disk plane of M31 is set to be the x-y plane of a simulation. The dE,N orbiting M31 has the initial position of $(x, y, z) = (R_{\rm apo}\cos\theta, 0, R_{\rm apo}\sin\theta)$ and the initial velocity of $(v_{\rm x}, v_{\rm y}, v_{\rm z}) = (0, \alpha V_{\rm c}, 0)$, where $R_{\rm apo}$, θ, and $V_{\rm c}$ are the apocenter of the orbit, the inclination angle with respect to the M31's disk (i.e., the x-y plane), the circular velocity at the apocenter, and the parameter ($0 \leq \alpha \leq 1$) that determines the orbital eccentricity represented by $e_{\rm p}$ (i.e, the larger α is, the more circular the orbit is). G1 is observed to have the projected distance of 40 kpc from M31 and radial velocity of −31 km s^{-1} with respect to M31 (e.g., Meylan et al. 2001). Guided by these observations, we investigate the models with $\theta = 30°$ and 80°, $R_{\rm apo}$ = 40, 80, and 160 kpc, and $e_{\rm p}$ = 0.62 (α = 0.5) and 0.18 (α = 0.9). We however describe the four representative and important models in this paper and the parameter values in these models (e.g., "fiducial model") are given in Table 1. All the simulations have been carried out on a GRAPE board (Sugimoto et al. 1990) with the particle number of 90000.

3. Results

Figures 1 summarizes the morphological evolution of the envelope and the nucleus of the dE,N in the fiducial model, which shows typical behavior in morphological transformation from a dE,N into G1. As the dE,N approaches the pericenter of its orbit, the strong global tidal field of M31 stretches the envelope of the dE'N along the direction of the dwarf's orbit and consequently tidally strips the stars of the envelope (T = 0.6 Gyr). The dark matter halo, which is more widely distributed than the envelope due to its larger core radius, is also efficiently removed from the dE,N during the pericenter passage. Since the envelope (and the dark matter halo) loses a significant fraction of its mass during the passage through the pericenter, the envelope becomes more susceptible to the tidal effects of M31 after the pericenter passage. Therefore, each subsequent time the dwarf approaches the pericenter, it loses an increasingly larger fraction of its stellar envelope through tidal stripping. Finally, the envelope and the dark matter halo lose 98 % and 99 % of their initial masses, respectively, after four passages through the pericenter (T = 4.8 Gyr).

Fig. 1. *Upper four*: Morphological evolution of the stellar envelope of the dE,N projected onto the *x-z* plane (i.e., edge-on view) for the fiducial model. For comparison, the M31 disk and bulge components are shown in the upper left panel and the disk size is indicated by a solid line in other three panels. The orbit of the dE,N with $R_{\rm apo} = 80$ kpc and $e = 0.62$ is indicated by a dotted line in the upper left panel. The time T (in units of Gyr) indicated in the upper left corner of each frame represents the time elapsed since the simulation starts. Each frame is 164 kpc on a side. *Lower four*: Morphological evolution of the stellar envelope and the nucleus of the dE,N projected onto the *x-y* plane (i.e., face-on view) for the fiducial model. Each frame is 20 kpc on a side.

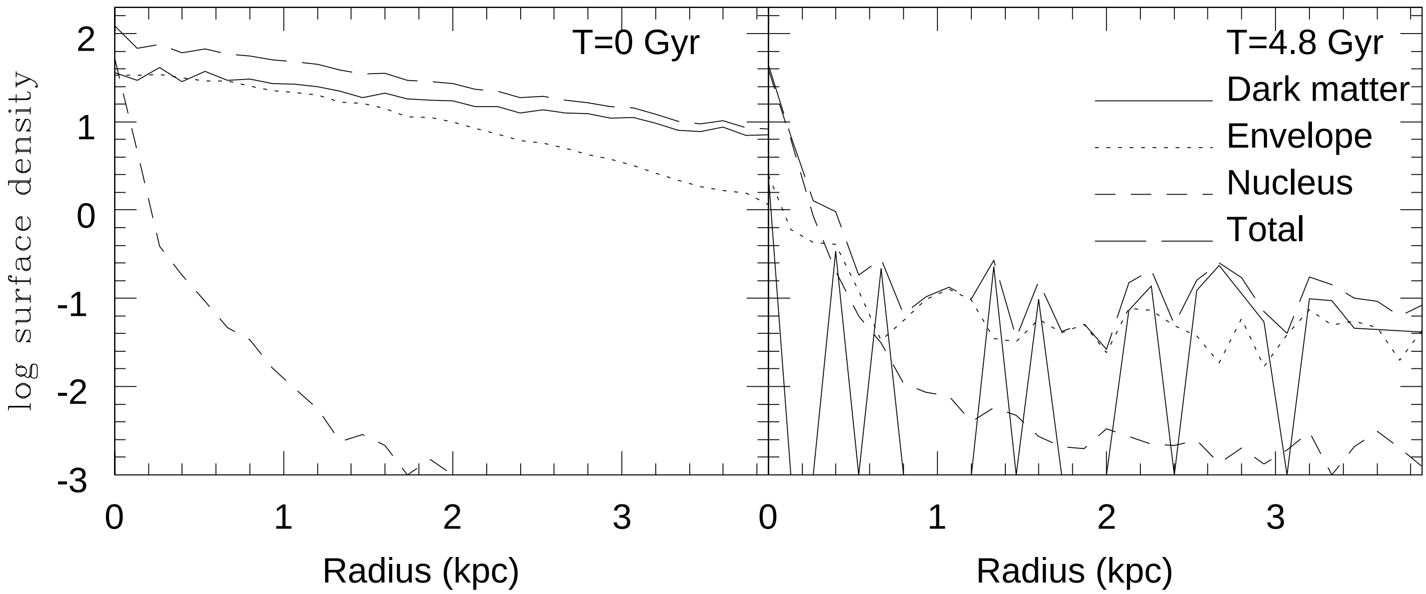

Fig. 2. The projected surface density profiles for the dark matter (*solid* line), the stellar envelope (*dotted* line), the nucleus (*short-dashed* line), and all these components (*long-dashed* line) at $T = 0$ Gyr (*upper* panel) and 4.8 Gyr (*lower* panel) in the fiducial model.

The central nucleus, on the other hand, is only weakly influenced by the tidal force as a result of its compact configuration. Because of its strongly self-gravitating nature, the nucleus loses only a small amount ($\sim$ 7%) of its mass and thus maintains its compact morphology during its tidal interaction with M31. As a result, a very compact stellar system with a negligible amount of dark matter is formed from the dE,N by $T = 4.8$ Gyr. The total nuclear stellar mass of the remnant within $5a_{\rm dw}$ is $\sim 1.5 \times 10^7\ M_{\odot}$, consistent with the observed mass of G1. The mass-to-light ratio, $M/L_{\rm B}$, decreases dramatically from ~ 10 to ~ 3 for $r < 5a_{\rm dw}$ within 4.8 Gyr. This result clearly explains why G1 is observed to have mass-to-light ratios that are much smaller than those observed for dE,Ns ($\sim$ 10): galaxy threshing is most efficient in the outer regions of a dE,N where the dark matter halo dominates gravitationally. As is shown in Figure 2, both the surface density of the dark matter and that of the envelope drop by more than an order of magnitude within 4.8 Gyr. If the initial central surface brightness of the dE,N is $\mu_B = 23\,{\rm mag\,arcsec^{-2}}$, then the final surface brightness of the dE,N at $r = 3$ kpc is about $\mu_B = 29.5\,{\rm mag\,arcsec^{-2}}$. Such a faint, low surface brightness envelope will be hard to detect, even by existing large ground-based telescopes.

The stripped stars from the envelope of the G1 progenitor dE,N form substructures and tidal tails in M31 halo region. Figure 3 shows that the tidal tail is a “rosette”, reflecting the dE,N eccentric orbit ($e_{\rm p} = 0.62$). Most of the stellar components of the tail can be regarded as being located well outside the M31 inner halo with $r < 40$ kpc ($\sim$ three degrees). The B–band surface brightness ($\mu_{\rm B}$) of the tail ranges from 28.7 mag arcsec^{-2} to 30.4 mag arcsec^{-2} with a mean of 30.1 mag arcsec^{-2}. These results imply that the tidal streams formed from the G1 progenitor dE,N would be hard to detect in previous observations by Ibata et al. (2001) and Ferguson et al (2002) that mapped the M31 halo region within $r \sim 40$ kpc.

Morphological properties of tails and substructures developed during tidal destruction of a G1 progenitor dE,N depend not only on the initial orbit but also on the dark matter structure of the dE,N. Figure 4 summarizes the following three dependences. Firstly, for the model with a smaller $e_{\rm p}$ (= 0.18), in which the time scale of morphological transformation from the dE,N into G1 is much longer than that of the fiducial model, the shape of the developed tail is more like a spiral than a rosette. Secondly, the distribution of stars in the developed substructures for the model with a smaller $R_{\rm apo}$ (= 40 kpc) appears to have a sharp boundary within which the stars can be located in a relatively homogeneous manner. Thirdly, the surface density of stars along the tail in the model with a more compact dark matter halo (with $a_{\rm dm} = 0.25\ a_{\rm dm,0}$) is much lower than that of the fiducial model owing to the smaller number of stripped stars. Formation of G1 from the dE,N does not occur in this model with $a_{\rm dm} = 0.25\ a_{\rm dm,0}$ which suggests that a dE,N with the high central density of the dark matter (such as seen in NFW models) are less likely to be a G1 progenitor dE,N (See Bekki et al. 2003 for more discussions on this point).

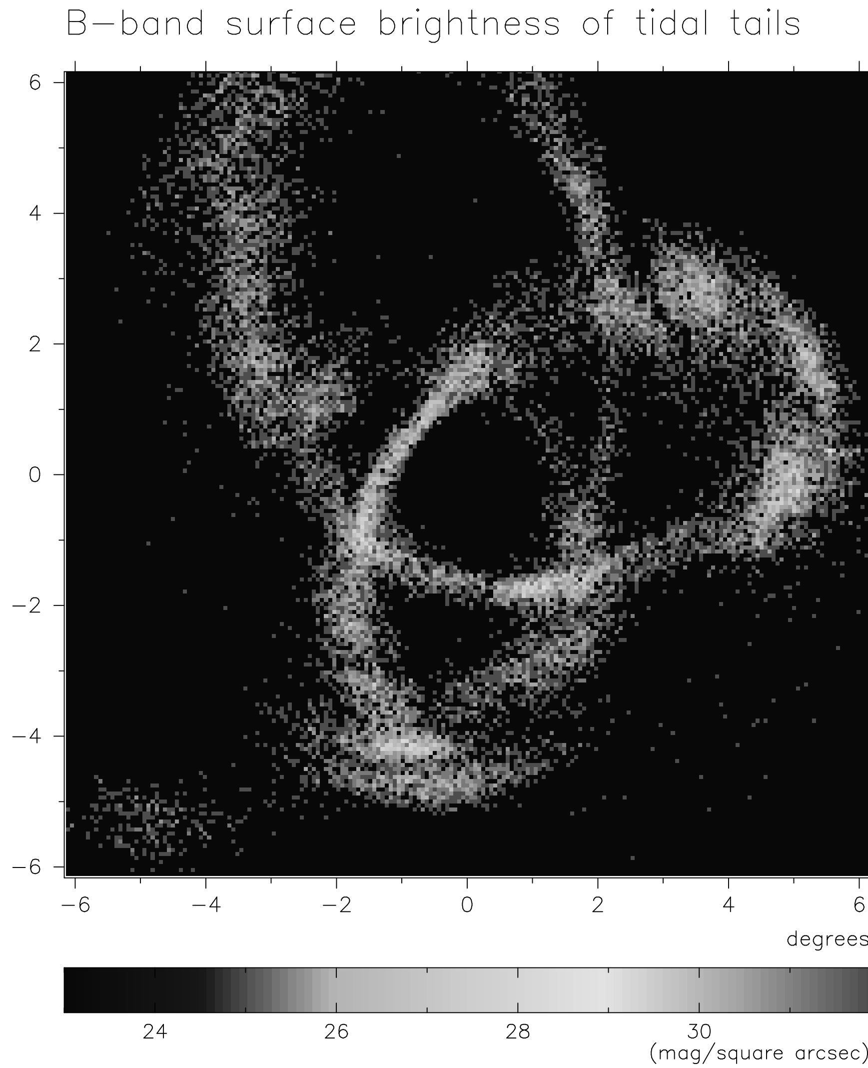

Fig. 3. The final B−band surface brightness μ_B (mag arcsec^{-2}) distribution projected onto the x-y plane for substructures/tails of M31's stellar halo developed from tidal destruction of the dE,N in the fiducial model. For comparison with observations by Ferguson et al. (2002), the scale is given in units of degree.

4. Discussion and conclusion

If G1 originates from a dE,N with $M_{\rm B} = -15$ mag, the mean metallicity of the M31 stellar halo consisting of stars stripped from the dE,N is roughly estimated as [Fe/H] = −0.96 (for $B - V = 0.71$ in the dE,N) using the observed metallicity-luminosity relation for dwarf galaxies, [Fe/H]=−3.43(±0.14) − 0.157(±0.012)$\times M_V$ (e.g., Côté et al. 2000). Because of its small mass (less than 10^9 $M_{\odot}$) and low metallicity, the stellar halo formed from the tidal destruction of the G1 progenitor dE,N could not be the major component of the observed high density and metal-rich ([m/H] ∼ −0.5) M31' stellar halo (Durrell et al. 2000). Also, relatively metal-rich components ([Fe/H] ∼ −0.7) of the stellar tail recently discovered in the M31 halo region (Ibata et al. 2001) might be less likely to be formed from the metal-poor stars stripped from G1's progenitor dE,N.

Recently Ferguson et al. (2002) discovered a stellar halo substructure located in the proximity of G1 (referred to as "G1 clump") and showed that total V−band magnitude and V−band surface brightness of the G1 clump can be estimated to be −12.6 mag and 28.5 mag arcsec^{-2}, respectively, for reasonable assumptions of dust extinction. The present study has demonstrated that metal-poor ([Fe/H] ∼ −1) and low surface brightness (μ_B ∼ 30 mag arcsec^{-2}) stellar halo substructures can be formed along the orbit of the G1 progenitor. We have also found that the stars in substructures close to the simulated G1 have orbital properties similar to those of the G1. Accordingly, future spectroscopic observations on radial velocities and metallicities of stars in the G1 clump will provide a new clue to the problem of whether the G1 clump can be tidal debris of the G1 progenitor dE,N.

Our simulations suggest that if a dE,N has a higher central dark matter density (i.e., more compact core), it cannot be transformed into a giant globular cluster (G1) because of the survival of its stellar envelope. Whether a dE,N can be transformed into a globular cluster by the M31 tidal field (i.e., by galaxy threshing) depends on whether the M31 tidal force is stronger than the self-gravitational force of the dark matter halo of the dE,N *at the pericenter* of the orbit of the dE,N. Therefore

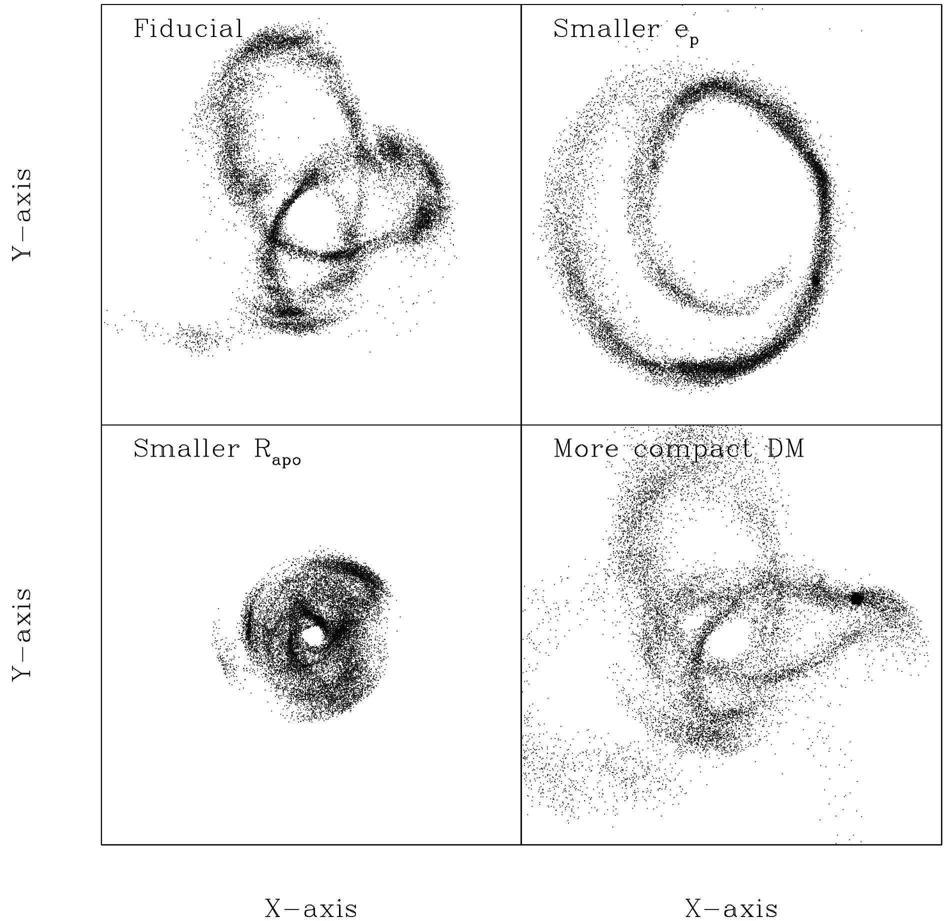

Fig. 4. Final mass distributions projected onto the *x*-*y* plane at T = 4.8 Gyr for the fiducial model (upper left), the smaller $e_{\rm p}$ one with $e_{\rm p}$ = 0.18 (upper right), the smaller $R_{\rm apo}$ with $R_{\rm apo}$ = 40 kpc (lower left), and the more compact dark matter model with $a_{\rm dm}$ = $0.25a_{\rm dm,0}$ (lower right). Each frame is 240 kpc on a side.

we can give *the upper limit* of the central dark matter density of the G1 progenitor dE,N, if we know its pericenter distance from M31. The possible central density of the dark matter halo of ω Cen's progenitor dE,N is discussed in Bekki & Chiba (2003), based on the proper motion data of ω Cen.

Drinkwater et al. (2003) have recently discovered a new type of galactic object with effective radius of ~ 20 pc, M_V ~ −12 mag, and velocity dispersion of ~ 30 km s^{-1} in the Fornax Cluster. These ultra-compact dwarfs (UCDs) with M_V more than 1 mag brighter than that of G1 have been demonstrated to be formed by galaxy threshing in which dE,Ns with $M_V < -16$ mag can be transformed into UCDs owing to tidal stripping of the stellar envelopes of dE,Ns (Bekki et al. 2001, 2003). We thus suggest that UCDs and giant globular clusters such as G1 and ω Cen can be regarded as the same class of stellar objects: The total mass or luminosity of a progenitor dE,N is the main difference between UCDs and G1. However, the difference in the location on the $M_{\rm V}$-σ_0 relation between UCD and G1 cannot be explained simply by the galaxy threshing scenario (Bekki et al. 2003).

The present study suggests that if G1 is *not* close to the pericenter of its orbit around M31, the stripped stars from the G1 progenitor dE,N can be distributed throughout the M31 outer halo region with $R_{\rm p}$ > 40 kpc. Therefore, future observations on M31's stellar halo need to extend to the current limit of previous surveys ($R_{\rm p}$ ~ 40 kpc; Ferguson et al. 2002) to reveal possible tidal streams and substructures formed from dE,N. Metallicity information of the possible streams and substructures in M31's outer halo is also useful to constrain the stellar population of the destroyed G1 progenitor dE,N. Thus, future deep, high-resolution, wide-area surveys of M31's *outer* ($R_{\rm p}$ > 40 kpc) stellar halo by wide-field cameras on large ground-based telescopes (e.g., Suprime-Cam on Subaru) will enable us to determine whether G1 originates from an ancient dE,N orbiting M31.

Acknowledgements. K.B. acknowledges the Large Australian Research Council (ARC). All the simulations described here were performed with GRAPE 5 systems at the National Astronomical Observatory in Japan.

References

Bekki, K., Couch, W. J., Drinkwater, M. J. 2001, ApJL, 552, 105
Bekki, K., Couch, W. J., Drinkwater, M. J., & Shioya, Y. 2003, MNRAS, 344, 399
Bekki, K., & Chiba, M. 2003, in preparation
Bekki, K., & Freeman, K. C. 2003, accepted in MNRAS
Binggeli, B., & Cameron, L. M., 1991, A&A, 252, 27

Burkert, A. 1994, MNRAS, 266, 877
Côté, P., Marzke, R. O., West, M. J., & Minniti, D. 2000, ApJ, 533, 869
Dinescu, D. I. 2002, in ASP Conf. Ser. 265 Omega Centauri, A Unique Window into Astrophysics. ed. F. van Leeuwen, J. D. Hughes, and G. Piotto (San Francisco: ASP), 608
Djorgovski, S. G., Gal, R. R., McCarthy, J. K., Cohen, J. G.; de Carvalho, R. R., Meylan, G., Bendinelli, O., & Parmeggiani, G. 1997, ApJ, 474, L19
Drinkwater, M. J., Gregg, M. D., Hilker, M., Bekki, K., Couch, W. J., Ferguson, J. B., Jones, J. B., Phillipps, S. 2003, Nature, 423, 519
Durrell, P. R., Harris, W. E., & Pritchet, C. J. 2000, AJ, 121, 2557
Ferguson, A. M. N., Irwin, M. J., Ibata, R. A., Lewis, G. F., & Tanvir, N. R 2002, AJ, 124, 1452
Ferguson, H. C., Bingelli, B. 1994, A&ARv, 6, 67
Freeman, K. C. 1993, in The globular clusters-galaxy connection, edited by Graeme H. Smith, and Jean P. Brodie, ASP conf. ser. 48, p608
Gebhardt, Karl, Rich, R. M., & Ho, L. C. 2002, ApJ, 578, L41
Gnedin, Oleg Y., Zhao, H., Pringle, J. E., Fall, S. M., Livio, M., & Meylan, G. 2002, ApJ, 568, L23
Hilker, M. & Richtler, T. 2000, A&A, 362, 895
Ibata, R. Irwin, M. Lewis, G, Ferguson, A. M. N., & Tanvir, N. 2001, Nature, 412, 49
King, I. R. 1962, AJ, 67, 471
Meylan, G., Jablonka, P., Djorgovski, S. G., Sarajedini, A., Bridges, T., & Rich, R. M. 1997, BAAS, 29, 1367
Meylan, G., Sarajedini, A., Jablonka, P., Djorgovski, S. G., Bridges, T., & Rich, R. M. 2000, BAAS, 32, 1440
Meylan, G., Sarajedini, A., Jablonka, P., Djorgovski, S. G., Bridges, T., & Rich, R. M. 2001, AJ, 122, 830
Mizutani, A., Chiba, M., & Sakamoto, T. 2003, ApJ, 589, L89
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
Rich, R. M., Mighell, K. J., Freedman, W. L., & Neill, J. D. 1996, AJ, 111, 768
Salucci, P., Burkert, A. 2000, ApJL, 537, 9
Sugimoto, D., Chikada, Y., Makino, J., Ito, T., Ebisuzaki, T., & Umemura, M. 1990, Nature, 345, 33
van den Bergh, S. 2000, The Galaxies of the Local Group
Zhao, H. S. 2002, in ASP Conf. Ser. 265 Omega Centauri, A Unique Window into Astrophysics. ed. F. van Leeuwen, J. D. Hughes, and G. Piotto (San Francisco: ASP), 391
Zinnecker, H., Keable, C. J., Dunlop, J. S., Cannon, R. D., & Griffiths, W. K. 1988, in Grindlay, J. E., Davis Philip A. G., eds, Globular cluster systems in Galaxies, Dordrecht, Kluwer, p603